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Prediction of part shape and associated material properties in hot-press forming using finite element analysis

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Abstract. The hot-press forming of a U-channel was conducted on a boron-steel blank. The die consisted of two separate parts in order to perform the partial quenching process. The cold die was initially at 25 °C while the heated die was set to five different temperatures, namely, 25, 120, 220, 320 and 400 °C. The cooling temperature history, Vickers hardness and springback of the channel were measured. A thermo-mechanical-metallurgical model, which accounts for the prior austenite deformation effect, was successfully implemented in the LS-DYNA explicit solver to simulate the hot-press forming process under partial quenching conditions. The predicted and experimental results were compared and found in reasonable agreement.

1. Introduction
The hot-press forming (HPF) process has drawn considerable attention in the automobile industry in order to produce ultra high-strength automotive components. This technology significantly contributes to lower the car weight, reduce gas emission and improve fuel efficiency. The HPF process consists of high temperature forming of a boron steel sheet (22MnB5) followed by die quenching. Although a full martensitic microstructure in the final product increases the strength, limited ductility results in lower crash performance. For this reason, the partial quenching method focuses to secure both the structural strength and ductility as in-service properties by tailoring the microstructure in press-hardened products. The purpose of this work is to simulate HPF and partial quenching of a 22MnB5 steel sheet sample.

2. Experiments

2.1. The blank and tool design
An S-rail shaped, U-draw bending die was designed to conduct HPF experiments with a partial quenching (PQ-HPF) method. The measurement of the temperature history during the whole process was recorded and further experiments were performed after the process to characterize hardness and springback of the partial quenched HPF parts. The geometry of the product is depicted in Fig. 1. In order to achieve PQ-HPF, the die was separated into three independent blocks with a 3 mm air gap between each other. Fig. 1(a) indicates that only the block corresponding to Zone (1) was heated up (heated die) while (2) and (3) were initially set to room temperature (cooled die). A 22MnB5 boron steel sheet sample provided by POSCO was investigated in this article.

2.2. Experiments with partial quenching die
In order to produce partially quenched products, the block corresponding to Zone (1) was heated up to five different temperatures, namely, 25, 120, 220, 320 and 400 °C. The others two blocks were kept to room temperature. This method allows variations of the cooling rate in the different zones of the channel. This results in gradients of microstructure, and mechanical properties such as strength, ductility and hardness. Fig. 2 summarizes the different steps of the experimental procedure. Before HPF, a 22MnB5

blank with an optimized shape was put into a furnace at 930 °C and kept for 300 seconds for full austenitization. Then, the blank was transferred and set on the press die within 10 seconds. The forming was conducted during 2 seconds, during which the material was still fully austenitic, and die quenched during 10 seconds. Finally, the die was opened to let the blank cool down in the air. In this work, the zone in the blank, which contacted the cooled die zone underwent rapid cooling, leading to a final martensite microstructure. In contrast, the zone in the blank in contact with heated die did not cool down as rapidly and resulted in a mixture of martensite and softer phases. A thermocouple was attached to the blank in this zone only to monitor the temperature history during the whole process. After PQ-HPF, hardness tests were conducted in each channel only near the heated zones.

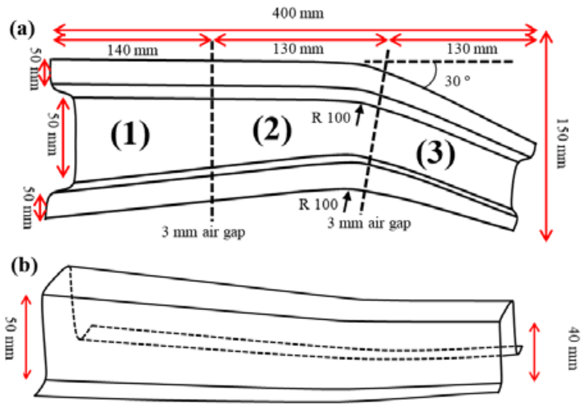

Figure 1. (a) Geometry of channel from rear view; (1) Section in contact with heated die; (2) & (3) Section in contact with cooled die), (b) Schematics of side view.

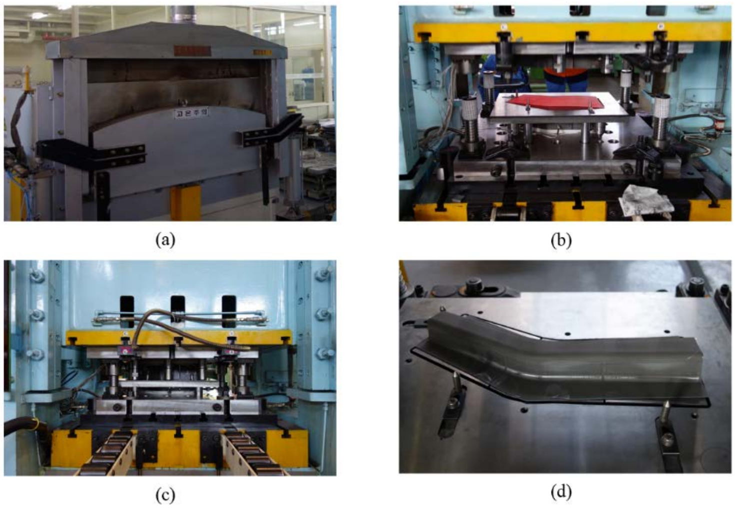

Figure 2. (a) Heating of blank in furnace (300 sec); (b) Transferring heated blank to die (10 sec); (c) Forming (2 sec) and die quenching (10 sec) and; (d) Air cooling (180 sec).

3. Verification of FE-user subroutine model

3.1. Implementation of user-subroutine for LS-Dyna

An approach, developed in-house by Bok [1] and tested successfully in the Abaqus user-subroutine interface, was successfully implemented in the LS-Dyna explicit solver. This new code allows coupled thermo-mechanical-metallurgical simulations and includes two main calculations, i.e., stress-strain field and phase evolution, since thermal aspects are taken care off by LS-Dyna. For the stress-strain field, von-Mises plasticity with isotropic hardening was combined with a modified Johnson-Cook law for the austenite phase and Swift for other phases. Three different strains were considered as a result of phase transformations, namely, thermal, volumetric and transformation plasticity strain. For the phase evolution, semi-empirical models were used. The Continuous Cooling Transformation (CCT) diagram was calculated using the Time Temperature Transformation (TTT) data. Since the steels transform under a continuously decreasing temperature field, a proper treatment to convert the incubation from isothermal to non-isothermal conditions is required [1].

3.2. Finite Element (FE) simulation

Finite Element (FE) simulations of the PQ-HPF of a U-draw bending were conducted to predict the temperature history, hardness and final shape of the product after springback. Fig. 3 shows the FE meshes for the tools and blank. The process conditions were similar to that of the real process. The cooled die was fixed as 25 °C and the heated die was set to 5 different temperatures, i.e., 25, 120, 220, 320 and 400 °C. Note that, since the blank transfer was not included in the simulations, the initial blank temperature was that measured at the beginning of the forming step. The heat transfer coefficients, which depend on the temperature difference between the blank and tools [2], were also adjusted for each condition. The heat transfer coefficients, measured in [2], ranged from 2500 to 8000 W/m^2 °C in this work.

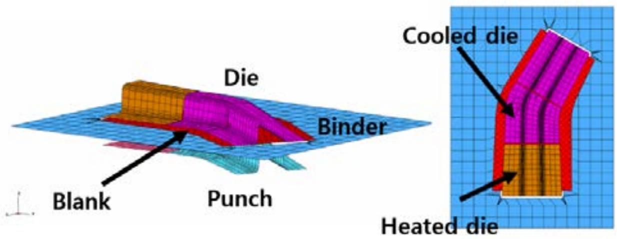

Figure 3. FE meshes of blank and tool for hot-press forming of U-channel.

3.3. Results

First of all, it is important to capture the temperature history in the blank because it is directly connected to the phase transformation, which mainly affects the mechanical property of the products. The experimental and predicted temperature histories are shown in Figs. 4(a) ~ (c). During the forming and quenching stages, the predicted temperatures are in good agreement with the experimental results. Only for an initial die at 400 °C in the air cooling stage (see the green line in Fig. 4(c)), a significant difference is observed because the latent heat was neglected in the FE model. The in-house user-subroutine cannot control the latent heat in the explicit LS-Dyna code. Actually the drastic temperature increase in the experiment indicates that bainite phase transformation occurred for this low cooling rate. In spite of this drawback, Fig. 4(d) demonstrates that the predicted hardness after air cooling was in quite good agreement with the experimental value for each die temperature. Thus, it is likely that neglecting the latent heat does not affect the predicted mechanical properties of the final products because the high cooling rate is the most important feature to capture in this work. Fig. 5 shows the predicted and experimental shapes of the channels after unloading. In this work, the springback was very low for all conditions in both simulations and experiments.

4. Conclusion

The present work aimed at predicting the material properties and shape in partial quenching HPF using a thermo-mechanical-metallurgical model in a FE analysis. The main conclusions of the present work are summarized below:

- The reliability of the model was successfully demonstrated, by the good agreement between the predicted and experimental temperature history, hardness and springback.

- Although most of the experimental and FE simulation results were in good agreement, the temperature history was not well predicted with the FE simulation for the heated die at 400 °C. This is because a significant amount of bainite transformation occurred due to the lower cooling rate but the corresponding latent heat was neglected in the simulation. However, this did not affect the predicted mechanical properties of the final product.

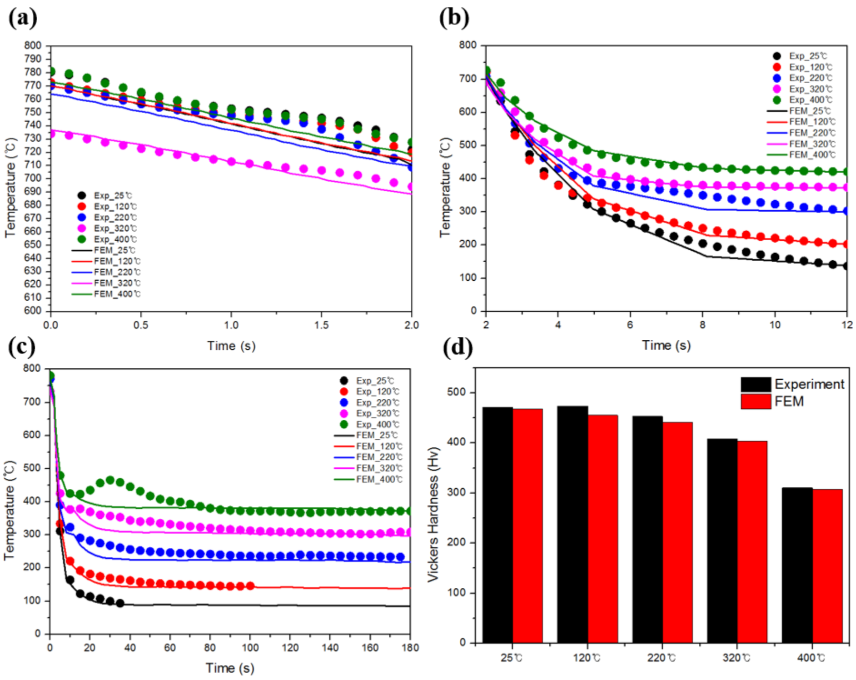

Figure 4. Experimental and predicted temperature history in the blank (a) During forming (0 ~ 2 sec); (b) During die quenching (2 ~ 12 sec); (c) During whole process (0 ~ 180 sec). (d) Experimental and simulated Vickers hardness after whole process.

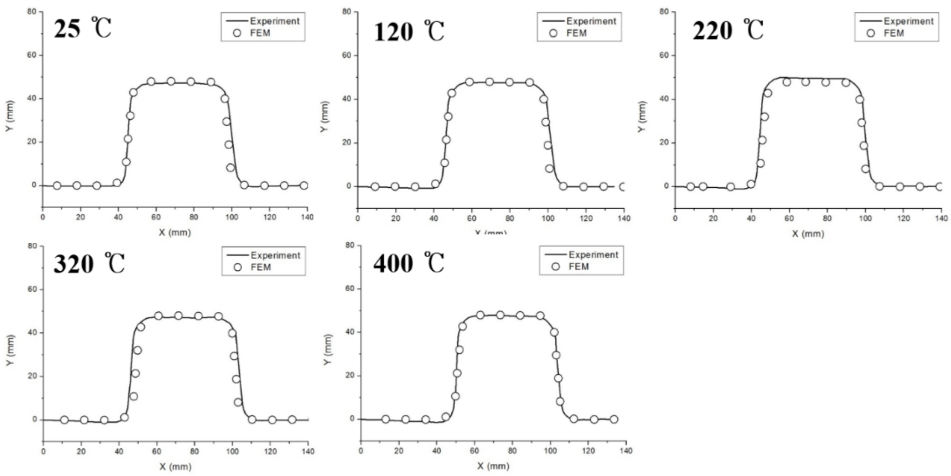

Figure 5. Springback prediction and comparison with experimental results.

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References

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